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Abstract

Electric Propulsion has found widespread acceptance by commercial satellite providers for on-orbit station keeping due to the total life cycle cost advantages these systems offer. NASA has also sought to benefit from the use of EP for primary propulsion onboard the Deep Space-1 and DAWN spacecraft. These applications utilized EP systems based on gridded ion thrusters, which offer performance unequaled by other electric propulsion thrusters. Through the In-Space Propulsion Project, a lower cost thruster technology is currently under development designed to make electric propulsion intended for primary propulsion applications cost competitive with chemical propulsion systems. The basis for this new technology is a very reliable electric propulsion thruster called the Hall thruster. Hall thrusters, which have been flown by the Russians dating back to the 1970s, have been used by the Europeans on the SMART-1 lunar orbiter and currently employed by fifteen other geostationary spacecraft. Since the inception of the Hall thruster, over 100 of these devices have been used with no known failures. This paper describes the latest accomplishments of a development task that seeks to improve Hall thruster technology by increasing its specific impulse, throttle-ability, and lifetime to make this type of electric propulsion thruster applicable to NASA deep space science missions. In addition to discussing recent progress on this task, this paper describes the performance and cost benefits projected to result from the use of advanced Hall thrusters for deep space science missions.

Introduction

One of the major objectives of the National Aeronautics and Space Administration (NASA) is robotic exploration of the solar system to search for evidence of life, to understand the history of the solar system, to search for resources, and to support future human exploration (ref. 1). The specific missions that are conducted to accomplish these goals are determined primarily based on prioritized recommendations from surveys of recognized scientists and experts in these fields (ref. 2). However, NASA's ability to accomplish these robotic space science missions is directly determined by the resources provided to the agency to perform these tasks. To reduce the cost of performing these missions or to enable missions that cannot currently be accomplished, NASA invests in the development of advanced technologies that support these science objectives. One particular advanced technology area that NASA invests in for this purpose is space propulsion.

The technology of advanced space propulsion is important to robotic solar system exploration primarily due to the challenges of sending spacecraft to distant destinations. This challenge can be met using two separate propulsion systems: a launch system capable of providing the thrust-to-weight required to achieve Earth orbit and an in-space propulsion system that can subsequently propel a spacecraft to its final destination. The technology utilized to launch spacecraft into Earth orbit has changed slightly over the last forty years. More importantly the cost of space launch has remained nearly constant over that time period at approximately \$10,000/kg, and is expected to remain at that level for the foreseeable future (ref. 3). Therefore, NASA's investment in space propulsion has targeted advanced in-space propulsion technologies that can offer dramatic improvements in propellant fuel economy relative to conventional state-of-art (SOA) systems.

These fuel efficient propulsion technologies, collectively referred to as electric propulsion, achieve this propellant saving, often described in terms of thrust per unit of mass flow, or specific impulse, by using electric power, generated on-board the spacecraft typically using a photovoltaic solar array. The benefits provided by high specific impulse include a significant reduction in the amount of propellant required to reach distant destinations from Earth orbit. This dramatically reduces overall launch mass, thereby enhancing or even enabling robotic solar system exploration missions. The disadvantages of these advanced propulsion technologies include: the low levels of acceleration they provide, which necessitate operation for thousands of hours to provide the total impulses needed to reach distant destinations; the cost, mass, and complexity of the electric propulsion and power systems; and the reduced solar irradiance available for photovoltaic power generation at the outer reaches of the solar system.

Within the commercial space industry the fuel saving capability provided by electric propulsion systems has been responsible for electric propulsion fully penetrating the geostationary communication satellite market. As can be seen in figure 1, there are currently 202 satellites that employ electric propulsion in orbit with 193 of those being geostationary satellites. The majority of these electric propulsion systems are being used for station keeping. Electric propulsion has become so prevalent for these applications as a direct result of the high power capability of these spacecraft, the increased payload capability, and increased spacecraft lifetime achievable by using fuel-efficient propulsion for station keeping. These benefits translate directly into financial gains for the operators of these spacecraft.

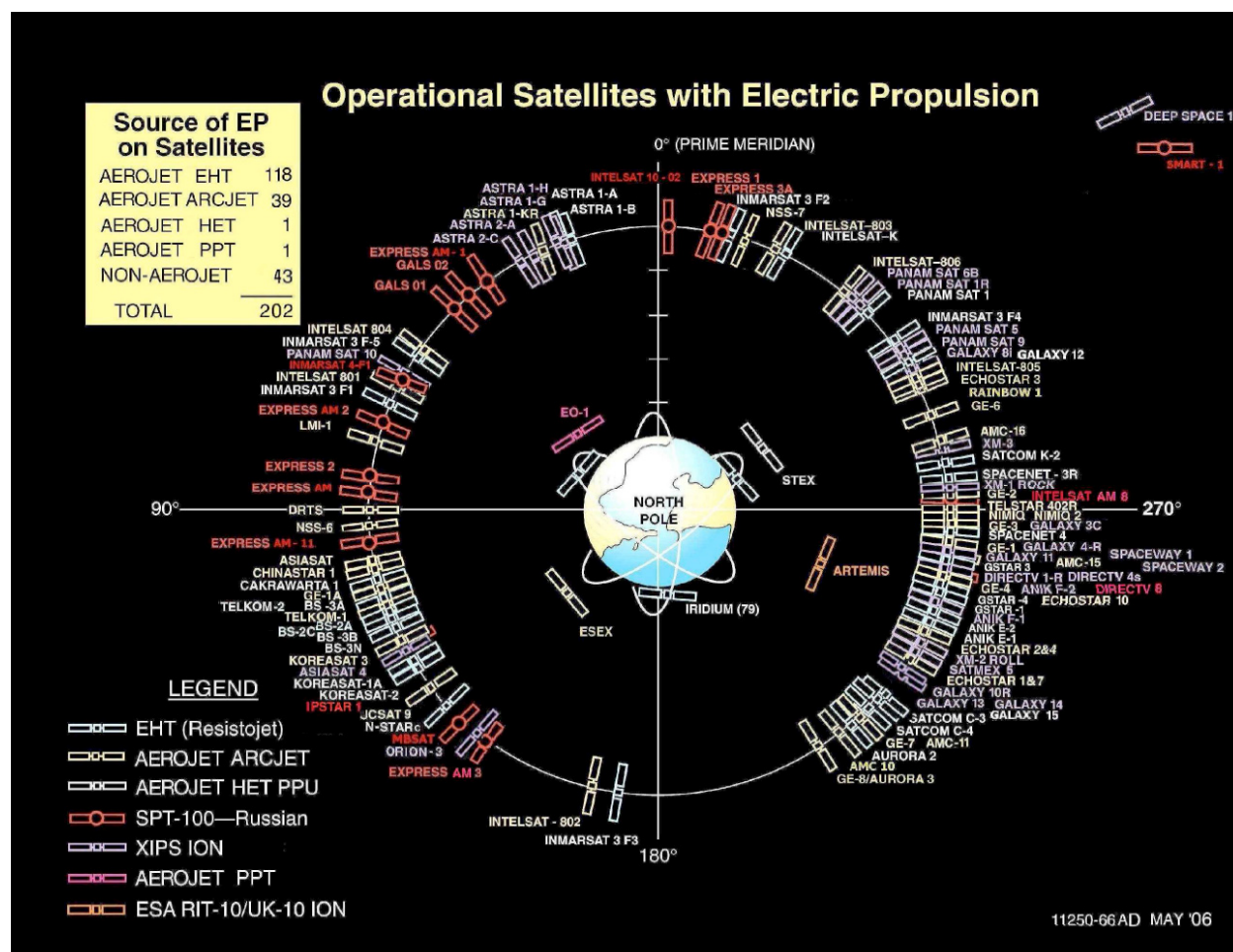


Figure 1.—Operational satellites currently utilizing electric propulsion (courtesy of the Aerojet Corporation).

In contrast to this, NASA has not pursued electric propulsion systems based solely on potential costs savings. NASA has pursued electric propulsion systems that enable missions that cannot practically be performed using any other type of primary propulsion. The first such system used for solar system exploration was the ion thruster system developed by the NASA Solar Electric Propulsion Technology Applications Readiness Program (NSTAR) (ref. 4). The Deep Space-1 spacecraft, launched in 1998, was able to image the Braille asteroid during a flyby and to gain scientific data during a rendezvous with the comet Borrelly (ref. 5). More recently NASA selected the Dawn mission to aid in the understanding of the conditions and processes present in the earliest epoch of the solar system. This mission will also utilize an NSTAR system to orbit asteroids 4 Vesta and 1 Ceres (ref. 6).

NASA continues the development of improved advanced electric propulsion technologies in order to increase their capability to perform missions such as Deep Space-1 and Dawn. These efforts are the responsibility of the In-Space Propulsion Technology Program, as part of NASA's Science Mission Directorate. The primary focus of this program is NASA's Evolutionary Xenon Thruster (NEXT) propulsion system. NEXT is an ion thruster system that improves upon NSTAR by: increasing the maximum operating power from

2.3 to 7 kW, increasing throttle-ability from a range of 5:1 to 10:1, increasing the maximum specific impulse from 3200 sec to over 4000 sec, and by increasing the thruster total impulse by a factor greater than three. The NEXT ion propulsion is on track to be readied for operational use as early as the end of 2007 (ref. 7).

In 2004 the In-Space Propulsion Technology Program conducted a study to quantify the potential benefit of using NEXT and NSTAR ion thruster systems and a proposed Hall thruster propulsion system for future robotic solar system exploration missions (ref. 8). This study considered both New Frontiers and Discovery class science missions; missions that are cost capped. A Hall thruster propulsion system was considered as part of this technology mission assessment study due to the cost savings offered by Hall thruster propulsion systems relative to ion thruster systems in the commercial arena. The characteristics of the Hall thruster system used in this analysis were derivative of the commercial Hall thruster systems, but relied on thruster improvements that would increase specific impulse, throttle-ability, and lifetime. The result of this study confirmed significant cost and performance advantages are achievable for NASA science missions if a Hall thruster propulsion system with the assumed characteristics is demonstrated. The In-Space Propulsion Technology Program reacted

to these results with the initiation of the High Voltage Hall Accelerator (HIVHAC) development task with the technical objective of increasing the maturity of advanced Hall thruster technology to provide NASA with these predicted mission benefits (ref. 9).

Since this time the HIVHAC task has been made steady progress towards demonstrating the technology needed for deep space science missions, the details of which are reported below. Also during this period two events occurred which have clearly illustrated the potential benefits of using Hall thruster propulsion for science mission and the potential pitfalls of using ion thruster propulsion systems for NASA science missions. In the 2003 the European Space Agency launched their Small Missions for Advanced Research in Technology 1 (SMART-1) Lunar probe as a secondary payload onboard an Ariane-5 (ref. 10). The SMART-1 spacecraft shown in figure 2 used a Hall thruster system with characteristics similar to those used for station keeping of geostationary communications to cost effectively place this small spacecraft in lunar orbit within 14 months of launch. This entire mission reportedly was performed for approximately €110 million Euros (approximately \$150 million) (ref. 11).

Simultaneously NASA's Jet Propulsion Laboratory experienced cost and schedule overruns during the fabrication of the Dawn spacecraft of such significance that the mission was at one point cancelled prior to its subsequent reinstatement. Schedule delays and more than \$73 million in cost overruns were in large part directly related to the NSTAR ion thruster system used by Dawn (ref. 12). In fact, more than \$40 million in cost overruns were directly related to the ion propulsion systems xenon tank and ion thruster power sources placing the cost of the Dawn ion propulsion system at more than \$50 million (ref. 13), a third of what the entire SMART-1 mission cost. While the problems with Dawn have all been resolved to NASA's satisfaction, and this mission is on schedule for a launch on June 30th of 2007, the comparison between these two missions offers a clear illustration of the benefits Hall propulsion may offer for future NASA science missions.



Figure 2.—The European Space Agency's Small Missions for Advanced Research in Technology 1 (SMART-1) Lunar probe.

NASA Hall Thruster Developments

Since its inception in 2003, the HIVHAC task has sought to develop Hall thruster technology that will meet the requirements of future NASA science missions while retaining the characteristics that have made Hall thruster propulsion systems cost-effective for Earth orbital applications. However, extending the capability of Hall thruster technology for deep space missions required significant technology improvements relative to SOA station-keeping Hall thrusters. The specific improvements required include throttle-ability to accommodate changes in power which occur throughout deep space missions, specific impulse of 2500 sec or greater to accommodate the high fuel economy needed to reach high Delta V destinations, and operational thruster lifetimes of 15,000 hr or longer to accommodate the mission propellant throughput with a minimum number of thrusters.

By 2005 the HIVHAC task had successfully demonstrated a prototype thruster that could provide specific impulses up to 2800 sec and could throttle over a range of input powers from 0.2 to 2.8 kW. This prototype thruster, shown in figure 3, resulted in further investment by the In-Space Propulsion Technology Program to develop a second thruster that could provide the required thruster lifetime while retaining the performance characteristics demonstrated by the initial prototype. In 2006 a new thruster was designed and fabricated with characteristics designed to allow it to meet all the requirements of future NASA science missions. Based on additional mission analysis the size of this new thruster was increased slightly relative to the initial thruster to improve mission capture. To date the new thruster has been performance tested over a range of input powers from 0.3 to 3.5 kW and is currently undergoing a long duration wear test to demonstrate the mission throughput required to reach high Delta V destinations. The measured specific impulse and thruster efficiency are shown in figure 4.



Figure 3.—The NASA-77M prototype thruster.

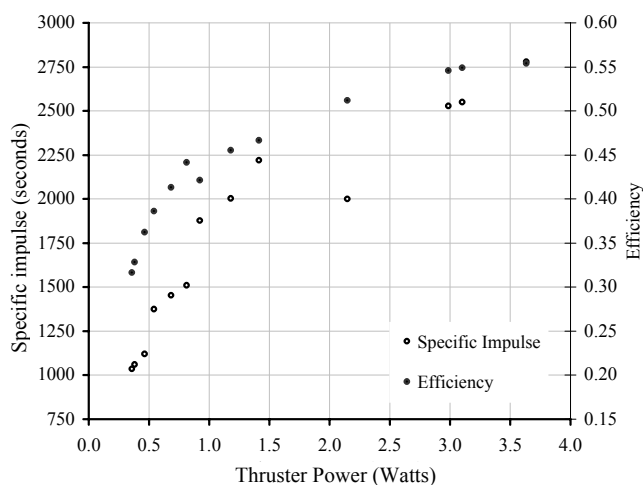


Figure 4.—Measured specific impulse and efficiency.

As of May 2007 the wear test had demonstrated operation of this second thruster at full power for a total of 1600 hr. The full power operating point corresponds to a discharge current of 5 A and a discharge voltage of 700 V. In comparison the operating conditions of the thruster used by the SMART-1 spacecraft and SOA Hall thrusters on-board geostationary communication satellites is 4.5 A and 300 V. The increased operating voltage of the NASA Hall thruster presents a significant challenge with respect to thruster lifetime because this voltage determines the energy of the xenon ions accelerated by the thruster to provide thrust. It is the impingement of these energetic ions upon the thruster that cause the thruster to wear. Ultimately this erosion phenomenon is what determines a thruster's lifetime. The HIVHAC team is developing a thruster that will have twice the lifetime of SOA Hall thrusters while producing ions with nearly twice the ion energy of SOA thrusters. This dramatic increase in lifetime is the result of a design innovation incorporated into this second NASA Hall thruster, which will be fully validated within the next 1000 hr of thruster operation.

Mission Benefits

The motivation for the development of this Hall thruster for NASA science missions were the dramatic cost savings that could be achieved relative to traditional ion propulsion

systems. The recurring cost estimated for a Hall thruster system capable of performing the DAWN mission was \$5.7 million (ref. 8), an order of magnitude less than the system Dawn used. These cost savings, achieved primarily as a result of the inherent simplicity of Hall thrusters and Hall thruster systems relative to other types of high performance electric propulsion, make this technology cost effective even when compared to chemical propulsion systems. In order to achieve these cost savings an additional non-recurring investment in a system development will be required. The In-Space Propulsion Technology Program plans to pursue a system development pending the validation of the NASA Hall thruster's life extending innovation.

As stated previously, the primary motivation behind the development of this propulsion technology was to improve the economics of utilizing electric propulsion. Despite this, mission analyses have shown there are also significant performance benefits that can be achieved by the use of Hall thruster propulsion systems relative to ion thruster propulsion systems (ref. 14). These benefits are typified by the analysis of a near Earth asteroid sample return mission with generic destination and launch dates. The mission targeted asteroid Nereus. The mission scenario considered launch to Earth escape with use of the solar electric propulsion system to rendezvous with the asteroid Nereus. The spacecraft then remained in the asteroid's vicinity for 90 days before using the solar electric propulsion system to return to Earth, conduct a flyby, and release the sample for direct re-entry. The basic characteristics of this mission are shown in table 1.

The overall mission analysis results for the near Earth asteroid sample return mission are shown in table 2. The total mass returned to Earth prior to sample return includes the propulsion system, payload, solar arrays, Earth return vehicle, and main spacecraft bus. Both single and multi-thruster operation

TABLE 1.—NEAR EARTH ASTEROID SAMPLE RETURN MISSION SUMMARY

Target body	Nereus
Launch vehicle	Delta 2925
Power system	6 kW solar array at 1 AU
Bus power	300 Watts
Launch year	2007/08
Thruster duty cycle	90%
Launch and rendezvous Dates	Selected by Optimizer

TABLE 2.—NEAR EARTH ASTEROID SAMPLE RETURN MISSION ANALYSIS RESULTS

Parameter	1 NSTAR thruster	1 Hall thruster	2 NSTAR thrusters	2 Hall thrusters
Trip Time,	3.23 yr	3.15 yr	3.15 yr	3.13 yr
C_3	10.2 km ² /s ²	4.9 km ² /s ²	2.0 km ² /s ²	1.9 km ² /s ²
Final delivered mass	664 kg	736 kg	857 kg	851 kg
Launch mass	996 kg	1112 kg	1183 kg	1186 kg
Drop mass (at Nereus)	140 kg	140 kg	140 kg	140 kg
Propellant throughput	191 kg	235 kg	186 kg	195 kg
Free space ΔV	6.5 km/s	6.2 km/s	5.2 km/s	4.7 km/s
Earth entry velocity	14.9 km/s	14.5 km/s	13.9 km/s	13.6 km/s
Simultaneous operating thrusters	1	1	2	2

was considered. The single and dual NSTAR options both represent SOA systems. Single NSTAR operation has been flight demonstrated on Deep Space-1 and is the baseline for Dawn. Simultaneous operation of multiple thrusters has been flight demonstrated on commercial missions, but has not been demonstrated with the NSTAR thruster. Systems allowing multi-thruster operation are more complex and therefore have higher cost and propulsion system mass than single thruster equivalents. Note that in all cases, an extra thruster and power-processing unit was included on the spacecraft for redundancy. In some cases, an extra thruster was also required to meet xenon throughput requirements.

The results of the analysis indicate that a single Hall thruster can deliver over 70 kilograms more total mass than a single NSTAR thruster for this application. Because the projected Hall thruster system was lighter than the equivalent NSTAR system for this application, the mass available for payload was even greater.

Conclusions

The ability of using an electric propulsion system based on Hall thruster technology to perform NASA robotic solar system exploration missions is being developed as a result of the In-Space Propulsion Technology Program's HIVHAC development task. Developing a Hall thruster system based on the thruster presented here will improve NASA's capability to effectively perform robotic solar system exploration missions if benefits similar to those identified through prior mission analyses are achievable for a range of exploration missions. Additionally, the cost benefits offered by using a Hall thruster propulsion system are substantial enough to make electric propulsion cost competitive with chemical propulsion systems. This innovation is expected to dramatically increase NASA's future use of electric propulsion systems for science missions.

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